Analysis of the X-ray emission of nine *Swift* afterglows

A. Panaitescu,[1]* P. Mészáros,[2,3] N. Gehrels,[4] D. Burrows[2] and J. Nousek[2]

[1]*Space Science and Applications, MS D466, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

[2]*Department of Astronomy & Astrophysics, Pennsylvania State University, University Park, PA 16802, USA*

[3]*Department of Physics, Pennsylvania State University, University Park, PA 16802, USA*

[4]*NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA*

ABSTRACT

The X-ray light curves of nine *Swift* XRT afterglows (050126, 050128, 050219A, 050315, 050318, 050319, 050401, 050408 and 050505) display a complex behaviour: a steep $t^{-3.0\pm0.3}$ decay until ∼400 s, followed by a significantly slower $t^{-0.65\pm0.20}$ fall-off, which at 0.2–2 day after the burst evolves into a $t^{-1.7\pm0.5}$ decay. We consider three possible models for the geometry of relativistic blast-waves (spherical outflows, non-spreading jets and spreading jets), two possible dynamical regimes for the forward shock (adiabatic and fully radiative), and we take into account a possible angular structure of the outflow and delayed energy injection in the blast-wave to identify the models which reconcile the X-ray light-curve decay with the slope of the X-ray continuum for each of the above three afterglow phases. By piecing together the various models for each phase in a way that makes physical sense, we identify possible models for the entire X-ray afterglow. The major conclusion of this work is that a long-lived episode of energy injection in the blast-wave, during which the shock energy increases at $t^{1.0\pm0.5}$, is required for five afterglows and could be at work in the other four as well. For some afterglows, there may be other mechanisms that can explain the $t < 400$ s fast falling-off X-ray light curve (e.g. the large-angle gamma-ray burst emission), the 400 s to 5 h slow decay (e.g. a structured outflow), or the steepening at 0.2–2 day (e.g. a jet-break, a collimated outflow transiting from a wind with a r^{-3} radial density profile to a homogeneous or outward-increasing density region). Optical observations in conjunction with the X-ray can distinguish among these various models. Our simple tests allow the determination of the location of the cooling frequency relative to the X-ray domain and, thus, of the index of the electron power-law distribution with energy in the blast-wave. The resulting indices are clearly inconsistent with a universal value.

Key words: radiation mechanisms: non-thermal – shock waves – ISM: jets and outflows – gamma-rays: bursts.

1 INTRODUCTION

Pre-*Swift* observations of gamma-ray burst (GRB) afterglows have led to great strides in their theoretical interpretation, while leaving some major unanswered questions.

The radio, optical and X-ray emission of GRB afterglows exhibit a power-law decrease with time ($F_\nu \propto t^{-\alpha}$) from hours to tens of days after the burst, with the temporal index α consistent with the slope β of the power-law continuum ($F_\nu \propto \nu^{-\beta}$) within the framework of relativistic spherical blast-waves (Mészáros & Rees 1997) or of spreading relativistic jets (Rhoads 1999). The collimation of the GRB ejecta yields a steepening of the power-law decay when the relativistic beaming has decreased sufficiently that the jet boundary

becomes visible. Such a steepening has been observed for the first time in the optical light curve of the afterglow 990123 (Kulkarni et al. 1999). Since then, about 10 other afterglows have displayed an optical light-curve break at about 1 day after the burst. The achromaticity of a jet light-curve break has not been clearly proven by pre-*Swift* observations because the X-ray light curves were not monitored over a time long enough to capture the jet-break. Furthermore, the radio light curves were usually poorly sampled during the first day and strongly affected by interstellar scintillation. The observations of many X-ray afterglows by *Swift*, together with ground-based optical observations, will enable us to test achromaticity of the afterglow light-curve break, as appears to be the case for the afterglow 050525A (Blustin et al. 2005).

The quenching of the interstellar scintillation of the radio afterglow 970508 (Frail, Waxman & Kulkarni 2000) has confirmed that the source size increases as expected for a relativistic blast-wave,

*E-mail: alin@lanl.gov

providing another test for this model. The decrease of the scintillation has also been observed in the radio afterglows 991208, 021004 and 030329. Further testing has been prompted by the detection of the optical afterglows of GRBs 990123 and 021211 at very early times (Akerlof et al. 1999; Fox et al. 2003; Li et al. 2003), starting at about 100 s after the burst. The steep decays ($\alpha = 1.8$ and 1.6, respectively) exhibited by these afterglows in the first 20 min can be attributed to the GRB ejecta energized by internal shocks (Mészáros & Rees 1997, 1999) or by the reverse shock[1] caused by the interaction with the circumburst medium (CBM) (Sari & Piran 1999).

A significant discrepancy between afterglow observations and theoretical expectations exists for the radio afterglows of GRBs 991208, 991216, 000301c and 010222, whose decay over one to two decades in time is substantially slower than that of the optical emission (Frail et al. 2004; Panaitescu & Kumar 2004). A change in the blast-waves dynamics, such as the transition to semirelativistic dynamics, is not a possible explanation, because the different radio and optical decays are observed over time ranges which overlap substantially. Our analysis (Panaitescu & Kumar 2004) of these afterglows shows that evolving microphysical parameters cannot decouple the optical and radio decays. This decoupling may be achieved if there is an extra radio emission arising from some late ejecta, energized by a reverse shock. For the optical afterglow to remain unaffected, the incoming ejecta should not alter the dynamics of the blast-wave, i.e. they should carry less kinetic than that already existing in the swept-up CBM.

The *Swift* measurements of the X-ray afterglow emission, starting from 100 s after the burst, open new possibilities for testing the blast-wave model and for refining its details. The XRT 0.2–10 keV light curves of the nine X-ray afterglows (050126, 050128, 050219A, 050315, 050318, 050319, 050401, 050408 and 050505) presented by Campana et al. (2005), Chincarini et al. (2005) and Tagliaferri et al. (2005) have shown that some X-ray afterglows decay very fast ($F_x \propto t^{-3}$) within the first few minutes after the burst, as reported previously for the afterglows 990510 (Pian et al. 2001) and 010222 (in't Zand et al. 2001), followed by a slower decay phase ($F_x \propto t^{-2/3}$), and a break to a steeper decay ($F_x \propto t^{-5/3}$) at a later time, ranging from 1 h to 1 day. The purpose of this paper is to investigate what features of the blast-wave model are required to accommodate the various decays of these *Swift* X-ray afterglows.

Barthelmy et al. (2005) have shown that the very early, fast decay of the X-ray emission of the afterglows 050315 and 050319 can be understood as the GRB emission from the fluid moving at angles larger than the inverse of the forward shock's Lorentz factor. Due to the curvature of the emitting surface, this large angle emission arrives at the observer at an ever increasing time and ever decreasing frequency (Kumar & Panaitescu 2000). However, for two other *Swift* afterglows with an early, fast decaying X-ray emission (050126 and 050219A), Tagliaferri et al. (2005) have found that the 15–350 keV GRB emission extrapolated to the XRT 0.2–10 keV band (under the assumption that the burst power-law spectrum extends unbroken to lower energies) falls short of the flux measured at the beginning of the X-ray observations. If the burst spectrum has a break below 15 keV, below which it is harder, then the GRB extrapolated flux

would be even less. This suggests that the fast falling-off X-ray emission does not arise from the same mechanism as the burst itself, and that it may arise in the forward shock. Therefore, for at least these two last bursts, we will test whether the very early X-ray emission can have the same origin as the rest of the afterglow.

The steepening observed at later times is most naturally attributed to a collimated outflow (jet), hence we will test if the pre- and post-break X-ray light-curve indices and the spectral slopes are consistent with this interpretation.

2 THE X-RAY LIGHT-CURVE DECAY INDEX

For the dynamics and collimation of the relativistic blast-wave, we consider three cases: (i) a spherical GRB remnant, in the sense that observations were done at a time when the afterglow Lorentz factor Γ was larger than the inverse of the jet opening θ_j and, hence, the effects associated with collimation were not yet detectable; (ii) a jet whose edge is visible ($\Gamma\theta_j < 1$) and which does not expand laterally (because it is embedded in an outer outflow, but whose emission is dimmer) and (iii) a jet with sharp edges, which spreads laterally and is observed when $\Gamma\theta_j < 1$. These models will be named S, j and J, respectively.

At a frequency above that of the synchrotron peak, ν_i, the index α of the light-curve power-law decay depends on

(i) the index p of the power-law electron distribution with energy

$$\frac{dN}{d\epsilon} \propto \epsilon^{-p} , \tag{1}$$

(ii) the density stratification of the CBM, for which we assume a power-law profile

$$n(r) \propto r^{-s} \quad s < 3 , \tag{2}$$

which comprises a homogeneous CBM ($s = 0$) and a pre-ejected wind at constant speed and mass-loss rate ($s = 2$), the condition $s < 3$ being required for a decelerating blast-wave,

(iii) the location of the cooling frequency ν_c relative to the observing band. The ν_c is the synchrotron characteristic frequency corresponding to an electron energy for which the radiative (synchrotron + inverse Compton) time-scale is equal to the electron age.

The expressions for $\alpha(p, s)$ for the S model are given in Mészáros & Rees (1997) and Sari, Narayan & Piran (1998) for $s = 0$ and in Chevalier & Li (2000) for $s = 2$. Rhoads (1999) and Sari, Piran & Halpern (1999) have shown that, for the J model, $\alpha = p$, irrespective of the location of ν_c and CBM stratification. These and other results for the S and j models are summarized below.

2.1 Adiabatic afterglows

Because we will determine from observations the required structure of the CBM, i.e. the parameter S, we start from the most general expressions for the evolution with observer time t of the afterglow spectral properties: peak flux F_p, and frequencies ν_i and ν_c. As derived in Panaitescu & Kumar (2004), they are

$$(S, j) \quad \frac{d\ln\nu_i}{d\ln t} = -\frac{3}{2}, \quad \frac{d\ln\nu_c}{d\ln t} = \frac{3s - 4}{8 - 2s} \tag{3}$$

for both the S and j models (note that the evolution of ν_i is independent of s and that ν_c increases for $s < 4/3$, but decreases for $s > 4/3$,

$$(S) \quad \frac{d\ln F_p}{d\ln t} = -\frac{s}{8 - 2s} \tag{4}$$

for the *S* model and

$$(j) \quad \frac{\mathrm{d}\ln F_{\mathrm{p}}}{\mathrm{d}\ln t} = -\frac{6-s}{8-2s} \qquad (5)$$

for the *j* model. For the latter, the faster decay is due to that the jet area is a factor $(\Gamma\theta_{\mathrm{j}})^2$ smaller than that visible to the observer in the case of a spherical outflow.

The synchrotron afterglow continuum is $F_\nu \propto \nu^{-\beta}$ (Sari et al. 1998), where

$$\beta = \begin{cases} 1/2 & \nu_{\mathrm{c}} < \nu < \nu_i \\ (p-1)/2 & \nu_i < \nu < \nu_{\mathrm{c}} \\ p/2 & \nu_i, \nu_{\mathrm{c}} < \nu \end{cases}. \qquad (6)$$

We restrict our attention to the $\nu > \min\{\nu_i, \nu_{\mathrm{c}}\}$ cases, for which $\beta > 1/2$, as observed by XRT for the *Swift* X-ray afterglows. From equations (3)–(5), it is easy to obtain the synchrotron light-curve decay $F_\nu \propto t^{-\alpha}$:

$$(Sa) \quad \alpha(\nu_i < \nu < \nu_{\mathrm{c}}) - \frac{3}{2}\beta = \frac{s}{8-2s} = \begin{cases} -1/2 & s \to -\infty \\ 0 & s = 0 \\ 1/2 & s = 2 \\ 3/2 & s = 3 \end{cases} \qquad (7)$$

$$(Sc) \quad \alpha(\nu > \nu_{\mathrm{c}}) - \frac{3}{2}\beta = -\frac{1}{2} \qquad (8)$$

$$(ja) \quad \alpha(\nu_i < \nu < \nu_{\mathrm{c}}) - \frac{3}{2}\beta = \frac{6-s}{8-2s} = \begin{cases} 1/2 & s \to -\infty \\ 3/4 & s = 0 \\ 1 & s = 2 \\ 3/2 & s = 3 \end{cases} \qquad (9)$$

$$(jc) \quad \alpha(\nu > \nu_{\mathrm{c}}) - \frac{3}{2}\beta = \frac{2-s}{8-2s} = \begin{cases} 1/2 & s \to -\infty \\ 1/4 & s = 0 \\ 0 & s = 2 \\ -1/2 & s = 3 \end{cases}. \qquad (10)$$

From the above equations, it can be seen that the passage of the cooling frequency through the observing band steepens the afterglow decay by $\Delta\alpha = |4 - 3s|/(16 - 4s)$, which is at the most 1/4, in addition to softening the spectrum by $\Delta\beta = 1/2$ for $s < 4/3$ or hardening it by $\Delta\beta = -1/2$ for $s > 4/3$. The representative values chosen for s in these equations show that the observable quantity $\alpha - 1.5\beta$ has a stronger dependence on the CBM structure for $s \lesssim 3$ (winds) than for $s \sim 0$. The case $s = 3$ should be taken only as the $s \to 3$ limit; for $s = 3$ the outflow deceleration is not a power law in the observer time, instead $\Gamma \propto 1/\sqrt{\ln t}$.

For the *J* model, the (α, β) closure relation is

$$(Ja) \quad \alpha(\nu_i < \nu < \nu_{\mathrm{c}}) - 2\beta = 1 \qquad (11)$$

$$(Jc) \quad \alpha(\nu > \nu_{\mathrm{c}}) - 2\beta = 0. \qquad (12)$$

Equations (8), (10) and (12) are valid whatever is the location of the injection frequency. However, there are further constraints for the applicability of the $\nu_{\mathrm{c}} < \nu < \nu_i$ case: $\beta = 1/2$ for all models and $\alpha = 1/4, 1$ for the *S* and *J* models, respectively.

The models *S*, *j* and *J* with $\nu < \nu_{\mathrm{c}}$ will be designated as *Sa*, *ja* and *Ja* (the letter 'a' indicates that the electrons radiating synchrotron emission at the observing frequency are losing energy adiabatically), while the models with $\nu_{\mathrm{c}} < \nu$ will be called *Sc*, *jc* and *Jc* (where

the letter 'c' shows that the electrons radiating at ν are cooling radiatively). Note from equations (8), (11) and (12) that for the *Sc* and *J* models, the index α is independent of the medium structure, hence the type of CBM cannot be determined for these models.

2.2 Inverse Compton-dominated electron cooling

In the derivation of equation (3), we have ignored a multiplicative factor $(Y + 1)^{-2}$ (where Y is the Compton parameter) in the expression of ν_{c}. Therefore, equation (3) is valid if $Y < 1$ (i.e. the radiative cooling of the electrons emitting at ν_{c} is synchrotron-dominated) or if Y is constant (which corresponds to the $\nu_{\mathrm{c}} < \nu_i$ case, where the Y parameter depends only on the ratio of the electron and magnetic field energies). If $Y > 1$ and $\nu_i < \nu_{\mathrm{c}}$, the decrease of the Compton parameter with time leads to a faster increase or a slower decrease of ν_{c} than given in equation (3) and to a slower decay of the afterglow emission at $\nu > \nu_{\mathrm{c}}$. This case is most likely relevant for the 2nd X-ray afterglow phase, between the flattening and steepening times t_{F} and t_{S}, when the X-ray light curve may exhibit a slower decay than that resulting from equations (8), (10) and (12). The equations for the afterglow light curve at $\nu > \nu_{\mathrm{c}}$ for the $(Y > 1, \nu_i < \nu_{\mathrm{c}})$ case, derived by Panaitescu & Kumar (2001), lead to

$$(Sc, s = 0) \quad \alpha - \frac{3}{2}\beta = \begin{cases} -1/(4-2\beta) & p < 3 \\ -1 & p > 3 \end{cases} \qquad (13)$$

$$(Sc, s = 2) \quad \alpha - \frac{3}{2}\beta = \begin{cases} -\beta/(4-2\beta) & p < 3 \\ -3/2 & p > 3 \end{cases} \qquad (14)$$

$$(jc, s = 0) \quad \alpha - \frac{3}{2}\beta = \begin{cases} (4-3\beta)/(8-4\beta) & p < 3 \\ -1/4 & p > 3 \end{cases} \qquad (15)$$

$$(jc, s = 2) \quad \alpha - \frac{3}{2}\beta = \begin{cases} (1-\beta)/(2-\beta) & p < 3 \\ -1 & p > 3 \end{cases}. \qquad (16)$$

For simplicity, the results in equations (13)–(16) are given for the two most likely types of CBM structure – $s = 0$ and $s = 2$ – and not for any *S*. For the *J* model, α is quasi-independent on the stratification of the CBM:

$$(Jc) \quad \alpha - 2\beta = \begin{cases} (1-\beta)/(2-\beta) & p < 3 \\ -1 & p > 3 \end{cases}. \qquad (17)$$

The results given for $p < 3$ in equations (13)–(17) are valid also for $p < 2$ as long as the total electron energy is a constant fraction of the post-shock energy, which is equivalent to saying that the high-energy cut-off of the electron distribution, which must exist for a finite total electron energy, has the same evolution as the minimum electron energy, $\gamma_i \propto \Gamma$.

The above equations show that the passage of the cooling frequency through the observing domain slows the afterglow decay by $\Delta\alpha \geqslant -1/4$ for $s = 0$ and $\Delta\alpha \geqslant -5/4$.

2.3 Radiative afterglows

The temporal evolutions given in equations (3) and (5) were derived under the assumption of an adiabatic blast-wave. If the electron fractional energy is around 50 per cent and if the electrons cool radiatively ($\nu_{\mathrm{c}} < \nu_i$), then radiative losses become important. In this case, the afterglow emission decays faster than for an adiabatic GRB remnant, given the stronger deceleration, therefore radiative

blast-waves should be of importance for the fast decaying, very early *Swift* X-ray afterglows.

From (i), the dynamics of a fully radiative blast-wave ($\Gamma M = const$, where $M \propto nR^3 \propto R^{3-s}$ is the mass of the swept-up CBM) and using (ii) the scalings for the spectral characteristics ($\nu_{i,c} \propto \gamma_{i,c}^2 B \Gamma$, where $B \propto \Gamma n^{1/2}$ is the post-shock magnetic field strength, $\gamma_i \propto \Gamma$ is the electron energy, and $\gamma_c \propto \Gamma^3 r^{-2} B^{-3}$ is the energy of the electrons whose radiative cooling time-scale is equal to the dynamical time-scale; $F_p \propto \Gamma BM$ for the S model and $F_p \propto \Gamma^3 BM$ for the j model) and (iii) the relation between the observer time and blast-wave radius $r \propto \Gamma^2 t$, the following evolutions of the spectral characteristics can be derived:

$$(RS, Rj) \quad \frac{d \ln \nu_i}{d \ln t} = -\frac{24 - 7s}{14 - 4s} , \quad \frac{d \ln \nu_c}{d \ln t} = \frac{3s - 4}{14 - 4s} \tag{18}$$

$$(RS) \quad \frac{d \ln F_p}{d \ln t} = -\frac{6 - s}{14 - 4s} \tag{19}$$

$$(Rj) \quad \frac{d \ln F_p}{d \ln t} = -\frac{18 - 5s}{14 - 4s} . \tag{20}$$

Hereafter, radiative afterglows will be indicated with the letter 'R' preceding the specific model. Note from equation (18) that, just as for an adiabatic afterglow, the cooling frequency increases for $s < 4/3$ and decreases for $s > 4/3$.

The light-curve decay indices resulting from equations (6) and (18)–(20) are

$$(RSc) \quad \alpha(\nu_c < \nu < \nu_i) = \frac{16 - 5s}{28 - 8s} \tag{21}$$

$$(RSc) \quad \alpha(\nu_c < \nu_i < \nu) = \frac{24\beta - 4 - s(7\beta - 1)}{14 - 4s} \tag{22}$$

$$(Rjc) \quad \alpha(\nu_c < \nu < \nu_i) = \frac{40 - 13s}{28 - 8s} \tag{23}$$

$$(Rjc) \quad \alpha(\nu_c < \nu_i < \nu) = \frac{24\beta + 8 - s(7\beta + 3)}{14 - 4s} . \tag{24}$$

The condition $\nu_c < \nu_i$ required by radiative dynamics guarantees that the Compton parameter Y is constant, hence there are no further complications with the inverse Compton-dominated electron cooling, as it was the case for an adiabatic blast-wave. Given that, in the J model, the jet Lorentz factor decreases exponentially with radius (Rhoads 1999), the dynamics and light curves of a radiative jet should be close to those for an adiabatic jet (equations 11 and 12).

2.4 Structured Outflows

There are two other factors which can alter the afterglow decay index α. One is that the relativistic outflow can be endowed with an angular structure, where the ejecta kinetic energy per solid angle, $dE/d\Omega$, is not constant (Mészáros, Rees & Wijers 1998). The light-curve decay indices for an axially symmetric outflow with a power-law structure

$$\frac{dE}{d\Omega} \propto \theta^q, \tag{25}$$

where the angle θ is measured from the symmetry axis (which, for simplicity, is assumed to also be the direction towards the observer) are given in Mészáros et al. (1998) and Panaitescu & Kumar (2003). In this work, recourse to a structured outflow will be made only to explain afterglow decays which are slower than that expected for the

S model. Evidently, such structured outflows require $q > 0$. If the slow X-ray decay is preceded by a faster fall-off, then the index q changes to $q < 0$ close to the outflow axis, corresponding to the j or J models. If the slow X-ray decay is followed by a steepening, then, going away from the outflow axis, the index q changes to either $q = 0$ (if the steeper decay is accommodated by the S model) or $q < 0$ (if that steeper decay can be explained with the j and J models). Therefore, in the most general case, where the X-ray light curve exhibits a sharp decay followed by a slow fall-off and then a steeper dimming, the outflow should have a bright spot moving towards the observer, surrounded by a dim envelope (so that a steep decay is obtained when the spot edge becomes visible to the observer), which is embedded in a more energetic outer outflow (yielding the slower decay), whose collimation leads to the late steepening when the outflow boundary becomes visible.

The decay index for the synchrotron emission from a structured outflow can be derived as described in Panaitescu & Kumar (2003). For a power-law radial structure of the CBM and angular structure of the outflow, we obtain

$$\alpha(\nu_i < \nu < \nu_c) - \frac{3}{2}\beta = \frac{s - 0.5q[(3 - s)\beta + 6 - 3s]}{8 - 2s + q} \tag{26}$$

$$\alpha(\nu > \nu_i, \nu_c) - \frac{3}{2}\beta = -\frac{4 - s + 0.5q[(3 - s)\beta + 4 - s]}{8 - 2s + q}. \tag{27}$$

The above results are valid for

$$q > \tilde{q} \equiv -2(4 - s) \begin{cases} [3 + 2\beta - 0.5s(\beta + 3)]^{-1} & \nu_i < \nu < \nu_c \\ [3 + 2\beta - 0.5s(\beta + 1)]^{-1} & \nu_i, \nu_c < \nu \end{cases}, \tag{28}$$

because for $q < \tilde{q} < 0$ the emission from the outflow axis ($\theta = 0$), where the energy per solid angle would formally diverge, becomes dominant and sets another light-curve decay index. From equations (26) and (27), it follows that for a given CBM structure, the slowest decay that a structured outflow can produce is that obtained in the $q \to \infty$ limit:

$$\alpha_{min} = \begin{cases} -3 + 0.5(\beta + 3)s & \nu_i < \nu < \nu_c \\ -2 + 0.5(\beta + 1)s & \nu_i, \nu_c < \nu \end{cases}. \tag{29}$$

Hence, for a homogeneous medium ($s = 0$), the light curve from a structured outflow could rise ($\alpha_{min} < 0$). Evidently, the structured outflow model can be at work only if the above decay is slower than that observed, the condition $\alpha > \alpha_{min}$ leading to a constraint on the CBM structure:

$$s < s_{max} \equiv 2 \begin{cases} \dfrac{\alpha + 3}{\beta + 3} & \nu_i < \nu < \nu_c \\ \dfrac{\alpha + 2}{\beta + 1} & \nu_i, \nu_c < \nu \end{cases}. \tag{30}$$

Equations (26) and (27) give the outflow structural parameter which accommodates the observed light-curve index α and spectral slope β:

$$q = \begin{cases} \dfrac{(4 - s)(6\beta - 4\alpha + 3) + 5s - 12}{2\alpha + 6 - (\beta + 3)s} & \nu_i < \nu < \nu_c \\ \dfrac{(4 - s)(6\beta - 4\alpha) + 2s - 8}{2\alpha + 4 - (\beta + 1)s} & \nu_i, \nu_c < \nu \end{cases}. \tag{31}$$

2.5 Energy injection

Another process which can reduce the afterglow dimming rate is the injection of energy in the blast-wave (Paczyński 1998; Rees &

Mészáros 1998) by means of some ejecta which were ejected later than the GRB ejecta (a long-lived engine) or at the same time but with a smaller Lorentz factor, thus reaching the decelerating GRB ejecta during the afterglow phase (a short-lived engine). A delayed injection of energy into the afterglow can be due to the absorption of the dipole electromagnetic radiation emitted by a millisecond pulsar (Dai & Lu 1998; Zhang & Mészáros 2001) if such a pulsar was formed.

The addition of energy in the blast-wave mitigates its deceleration and, implicitly, the afterglow decay rate. Rees & Mészáros (1998) have derived the decay index α for an energy injection that is a power law in the ejecta Lorentz factor. The expressions for the index α for an energy injection which is a power law in the observer time,

$$E_i(<t) \propto t^e , \tag{32}$$

are given in equations (23), (24) and (30) of Panaitescu & Kumar (2004). From those equations, it follows that energy injection reduces the light-curve decay indices given in equations (7)–(12) by

$$(S-EI) \quad \Delta\alpha = e \begin{cases} \frac{1}{2}(\beta+2) - \dfrac{s}{8-2s} & \nu_i < \nu < \nu_c \\ \frac{1}{2}(\beta+1) & \nu_i, \nu_c < \nu \end{cases} \tag{33}$$

$$(j-EI) \quad \Delta\alpha = e \begin{cases} \frac{1}{2}(\beta+2) + \frac{2-s}{8-2s} & \nu_i < \nu < \nu_c \\ \frac{1}{2}(\beta+1) + \frac{1}{4-s} & \nu_i, \nu_c < \nu \end{cases} \tag{34}$$

$$(J-EI) \quad \Delta\alpha = \frac{2}{3}e \begin{cases} \beta+2 & \nu_i < \nu < \nu_c \\ \beta+1 & \nu_i, \nu_c < \nu \end{cases} \tag{35}$$

for the adiabatic S, j and J models.

Finally, all the decay indices given in the above equations were derived assuming that the microphysical parameters which determine the spectral characteristics (ν_i, ν_c, F_p) and the continuum slope (β), i.e. the parameters for the typical post-shock electron energy and magnetic field strength[2] and the power-law index p of the electron distribution with energy are constant. This possibility is not investigated in this work.

3 MODELS FOR *SWIFT* X-RAY AFTERGLOWS

As described in the Introduction, the *Swift* X-ray afterglows exhibit three phases: the 1st phase, lasting until $t_F \sim 300$ s, is characterized by a sharp decay; the 2nd phase, lasting until $t_S \sim 10^{3.5} - 10^5$ s, is marked by a much slower fall-off, while in the 3rd phase, the X-ray light curve displays a faster decay. The light-curve decay indices α and the spectral slopes β are listed for each phase in Table 1. The closure relations between α and β presented in Section 2 either provide a criterion for distinguishing among the various models that can accommodate the observed afterglow properties or allow the determination of the CBM structure. Since $s < 3$ is required for a decelerating blast-wave, this also serves as a test of the various models.

Table 1 lists the models for which the closure relations given in Section 2 between the light-curve decay index α and spectral slope β are satisfied within 1σ, for each afterglow decay phase. To find a model for the entire afterglow, these piece-wise models must now be put together in a sequence that makes sense and is not contrived.

[2] Yost et al. (2003) have shown that a decrease of the parameter for the magnetic field energy slower than $t^{-1/2}$ or an increase slower than $t^{3/4}$ is allowed for several afterglows.

The criteria by which we construct a model for the entire X-ray afterglow are as follows.

(i) Models relying on coincidences to accommodate two adjacent X-ray phases are excluded, i.e. only one factor (cooling frequency passage, change of CBM structure, region of non-monotonic variation in the energy per solid angle becoming visible, beginning/cessation of energy injection) at a time is employed to explain a variation of the X-ray decay index;

(ii) radiative outflows can evolve into adiabatic ones, but not the other way around,

(iii) any of the three dynamical models (S, j and J) can be followed by the same model, but only the S model can be followed by the j and J models, allowing for a collimated outflow, spreading or non-spreading, whose edge becomes visible to the observer;

(iv) the evolution of the cooling frequency ν_c required to join two models at t_F or t_S must be compatible with the CBM structural index S, i.e. ν_c can increase only if $s < 4/3$ and can decrease only if $s > 4/3$ (modulo the effect of a decreasing Compton parameter when electron cooling is dominated by inverse Compton scatterings).

A structured outflow or energy injection is invoked only when the X-ray decay during the 2nd phase ($t_F < t < t_S$) is too slow to be explained by the S, j and J models, for the CBM structured required to accommodate the X-ray decay preceding ($t < t_F$) or following ($t > t_S$) this phase:

(v) for the structured outflow model, a working condition is that the slowest decay that it would yield (equation 29), given the CBM structure which explains the X-ray emission at $t < t_F$ or at $t > t_S$ is slower than that observed. A structured outflow for the 2nd afterglow phase cannot be preceded by the J model, as the existence of an outflow outside the jet would prevent its lateral spreading,

(vi) for the energy injection model, we determine from equations (33)–(35) the index e (equation 32) which reconciles the slow X-ray decay with the spectral slope, for the model (S, j, or J) and CBM structure which accommodates the X-ray emission before ($t < t_F$) or after ($t > t_S$) the energy injection episode. The ratio E_I/E_0 of the total injected energy E_I to the energy E_0 existing in the blast-wave prior to the energy injection episode is $(t_{off}/t_{on})^e$ where t_{on} is the light-curve flattening time t_F or the epoch of the first measurement (if no flattening was observed) and t_{off} is the light-curve steepening time t_S or the epoch of the last measurement (if no steepening was observed). Then, a test of the energy injection model can be done if it is assumed that the pre-injection energy E_0 is comparable to the GRB 15–350 keV output. For this test, we calculate the injected energy E_I and require for the S model that the outflow kinetic energy contained within $10°$ (which is sufficiently wide to resemble a spherical outflow until 1 day after the burst) does not exceed 10^{53} erg. However, this test is based on the assumption that the ejecta producing the burst and the beginning of the X-ray afterglow emission are the same. This does not have to be the case, as it is possible that the GRB emission arises from internals shocks in the entire outflow and yet only its leading edge drives the forward shock and radiates at the beginning of the X-ray afterglow.

We allow a variable index S as we do not know what are the properties of the winds expelled by massive stars in the last 1000 yr before they explode, hence we do not know what is the density structure of the CBM within the first parsec, where the afterglow emission is produced. Variations in the GRB progenitor's mass-loss rate and wind speed could lead to a CBM with a structure different than the r^{-2} profile expected for a constant speed, constant mass-loss rate and to interactions between winds that could form shells of higher density.

Table 1. Models that accommodate the light-curve power-law decay index ($F_x \propto t^{-\alpha}$) and continuum power-law slope ($F_\nu \propto \nu^{-\beta}$) measured by *Swift* for the early ($\sim 10^2$ s), mid (10^3–10^4 s) and late ($\sim 10^5$ s) X-ray afterglow emission.

GRB	1st phase: $t < t_F$ – Steep decay			2nd phase: $t_F < t < t_S$ – Slow decay			3rd phase: $t_S < t$ – Fast decay		
	α_1	β_1	model	α_2	β_2	model	α_3	β_3	model
050126[a]	2.7±0.2	1.3±0.2	*Sa, ja, Rjc, Jc*	0.6±0.1	≃1.3	None			
050128[b]				0.3±0.1	0.6±0.1	*Sc (jc, RSc, Rjc)*	1.3±0.2	0.8±0.1	*Sa, jc, Jc (RSc, Rjc)*
050219A[c]	3.2±0.2	1.1±0.2	*Sa, ja, Ja*	0.8±0.1	≃1.1	*Sc (RSc, Rjc)*			
050315[a]	3.3±0.2	1.3±0.2	*Sa, ja*	0.7±0.1	0.9±0.2	*Sc, jc (RSc, Rjc)*	1.6–2.6	1.0±0.1	*Sa, ja, jc, Ja, Jc (RSc, Rjc)*
050318[a]				1.0±0.1	1.0±0.2	*Sa, Sc, jc, RSc (Rjc)*	1.4±0.3	1.2±0.3	*Sa, ja, jc, Jc (RSc, Rjc)*
050319[a]	3.0±0.2[d]	1.9±0.2	*Sa, jc, RSc, Rjc*	0.5±0.1	0.8±0.1	*Sc, jc, RSc, Rjc*	1.2±0.1	0.7±0.2	*Sa, jc, Jc (Rjc)*
050401[a]				0.5±0.1	1.1±0.1	None	1.6±0.1	1.1±0.1	*Sa, jc (RSc, Rjc)*
050408[a]				0.7±0.1	1.1±0.2	None	1.5±0.2	≃1.1	*Sa, jc (RSc, Rjc)*
050505[a]				0.7±0.2	1.0±0.1	*Sc, jc (RSc, Rjc)*	2.5±0.4	0.9±0.1	*Sa, ja, Ja (Rjc)*

References for α and β – [a]Chincarini et al. (2005), [b]Campana et al. (2005), [c] Tagliaferri et al. (2005)
[d] for $t = 0$ at the beginning of the second GRB peak (Barthelmy et al. 2005).
Model coding – *S*, spherical outflow; *j*, non-spreading jet; *J*, sideways spreading jet; *R*, radiative afterglow.
For models given in parentheses, the outflow is less likely to be radiative at ~ 1 day after the burst, or require a wind with a radial profile close to r^{-3}, for which the analytical results given in Section 2 are only approximate.
a: $\nu_x < \nu_c$ (X-ray emitting electrons are cooling adiabatically).
c: $\nu_c < \nu_x$ (X-ray emitting electrons are cooling radiatively).

Table 2. Possible models for the afterglow X-ray phases of Table 1.

GRB	$t < t_F$ – Steep decay		$t_F < t < t_S$ – Slow decay				$t_S < t$ – Fast decay		
	Model	s (1)	Model	s (1)	e (2)	q (3)	model	s (1)	p (4)
050126	*ja*	<2.5	EI		1.0–1.4				3.5±0.4
	ja	<2.5	SO	<1.7		>0.7			3.5±0.4
	Rjc	<3	EI		1.0–1.9				2.5±0.4
	Rjc	<3	SO	<2.3		>1.4			2.5±0.4
	Jc	<3	EI		1.4				2.5±0.4
050128			*Sc*	<3			*jc(Jc)*	<2.2(3)	1.2±0.1
			jc	3			*jc*	<0	1.2±0.1
050219A	*ja*	2.4–3	EI		1.7–2.3				3.2±0.4
	Ja	<3	EI		1.2				3.2±0.4
050315	LA–GRB		*Sc*	<3			*jc(Jc)*	<2.1(3)	1.9±0.1
050318			*Sc*	<3			*jc(Jc)*	<1.9(3)	2.1±0.1
			Sa	<−3			*Sa*	2	3.0±0.3
			jc	2.6–3			*jc*	→ −∞	2.1±0.1
050319	LA–GRB		*Sc*	<3			*jc(Jc)*	<2.1(3)	1.5±0.2
	LA–GRB		*jc*	3			*jc*	0	1.5±0.2
050401			EI		0.7		*Sa*	−1–0.6	3.1±0.1
			SO	<1.7		1.7–3.5	*Sa*	−1–0.6	3.1±0.1
			SO	<2.4		>1.1	*RSc*	<3	2.1±0.1
			EI		0.7		*jc*	1.6–2.4	2.1±0.1
			SO	<2.4		>3.2	*jc*	1.6–2.4	2.1±0.1
			EI		0.6		*Rjc*	2.7–2.9	2.1±0.1
050408			EI		0.4–0.6		*Sa*	<1.1	3.3±0.4
			SO	<1.8		>0.5	*Sa*	<1.1	3.3±0.4
			EI		0.4–0.6		*jc*	0.7–3	2.3±0.4
			SO	<2.5		>0.8	*jc*	0.7–3	2.3±0.4
050505			EI		>0.9		*ja/Ja*	<3	2.8±0.2
			SO	<1.9		>0.9	*ja*	-2–3	2.8±0.2

Model coding – EI: energy injection; SO: structured outflow; LA–GRB: large-angle ($\theta > 1/\Gamma$) GRB emission.
(1) Exponent of radial density profile (equation 2); for the SO model, the upper limit on s is that resulting from equation (30).
(2) Exponent of the energy injection law (equation 32) obtained from equations (33)–(35) for the index s required at $t < t_F$ or at $t > t_S$.
(3) Exponent of the angular distribution of the energy per solid angle (equation 25) obtained from equation (31) for the index s required at $t < t_F$ or at $t > t_S$.
(4) Exponent of the power-law distribution of electrons with energy (equation 2); this value is for all X-ray phases except LA–GRB.

By applying the above criteria, we arrive at the models given in Table 2. Below, we discuss in some detail the nine *Swift* X-ray afterglows and the models that accommodate them.

050126. The XRT light curve of this afterglow exhibits a steep fall-off until $t_F \gtrsim 300$ s, followed by a slower decay. Tagliaferri et al. (2005) have shown that extrapolation of the 15–350 keV Burst Alert Telescope (BAT) emission to the 0.2–10 keV X-ray Telescope (XRT) band is dimmer at 100 s than the observed XRT flux. Furthermore, the XRT spectrum ($\beta_1 = 1.26 \pm 0.22$) during the 1st phase is softer than the BAT spectrum ($\beta_\gamma = 0.32 \pm 0.18$), hence

the early X-ray afterglow is not the large-angle GRB emission and must be attributed to the forward shock. If there is no spectral evolution ($\beta_2 = \beta_1$) across t_F, as indicated by Tagliaferri et al. (2005), then the slow X-ray decay of the 2nd phase cannot be explained by a change in the structure of the CBM medium for any of the models (Sa, ja, Rjc, Jc) which accommodate the 1st phase. Conversely, if the CBM structure does not change across t_F, then the slower decay at the 2nd phase requires a substantial hardening of the spectrum, corresponding to a rising one ($\beta_2 < 0$) for the models Sa, ja and Rjc, or one with $\beta_2 = 0.20 \pm 0.25$ for the Jc model, both of which are inconsistent with the XRT observations. Furthermore, for the possible models for the 1st afterglow phase, the passage of the cooling frequency through the X-ray band can only steepen the afterglow decay. Hence, the most plausible models that can explain the flattening X-ray light curve of 050126 require energy injection or a structured outflow. The Sa model with either energy injection or a structured outflow does not satisfy conditions (v) and (vi) above.

050128. Although XRT observations started at 100 s after the burst, a steep early decay has not been observed (Campana et al. 2005). Its decay steepens at $t_S \gtrsim 10^3$ s without a spectral evolution. Of the many possible combinations of models for the 2nd and 3rd phases, the most plausible is that of a collimated outflow (jc and Jc models), leading to a steepening of the X-ray decay when the boundary of the jet becomes visible. Another possibility is that of non-spreading jet (jc model) which transits from a r^{-3} wind into a region of increasing density at t_S. We note that all these models require a rather hard electron distribution, with $p \lesssim 1.3$.

050219A. The features of this afterglow are similar to those of 050126. It exhibits a fast fall-off until $t_F \sim 300$ s, followed by a slower decay. The extrapolation of the 15–350 keV BAT emission to the 0.2–10 keV XRT band underpredicts the observed flux at 100 s (Tagliaferri et al. 2005) and the X-ray spectral slope ($\beta_1 = 1.1 \pm 0.2$) is much softer than that of the burst ($\beta_\gamma = -0.75 \pm 0.30$), hence the rapid, early fall-off of the 050219A X-ray afterglow is not the GRB large-angle emission. Just as for the afterglow 050126, a change in the CBM structure cannot explain the X-ray light-curve flattening. If the CBM structure is considered unchanged across t_F, then the slowing of the X-ray decay would require a rising spectrum ($\beta_2 < 0$) for the 2nd phase, which is inconsistent with the XRT observations. Because all models for the 1st afterglow phase require that the cooling frequency is above the X-ray domain, its passage is either impossible or it would steepen the light-curve decay. Consequently, the slower decay observed for the X-ray afterglow 050219A after t_F requires either energy injection or a structured outflow. Condition (v) is not satisfied by either the Sa and the ja models and a structured outflow, while the Sa model with energy injection requires too much energy.

050315. The X-ray emission exhibits a flattening at $t_F \lesssim 10^3$ s, accompanied by a hardening of the spectrum ($\beta_2 - \beta_1 = -0.41 \pm 0.21$), and followed by a steeper decay after $t_S \gtrsim 10^5$ s, across which there is no spectral evolution. Barthelmy et al. (2005) and Vaughan et al. (2005) have shown that the early, steep fall-off is consistent with the large-angle GRB emission: the extrapolation of the 15–350 keV BAT emission to the 0.2–10 keV XRT band matches the XRT flux measured at 100 s, the X-ray spectral slope ($\beta_1 = 1.34 \pm 0.15$) is comparable to that of the burst ($\beta_\gamma = 1.18 \pm 0.11$), and the X-ray decay index ($\alpha_1 = 3.35 \pm 0.19$) is close to the expected value ($2 + \beta_\gamma = 3.18 \pm 0.11$). The steepening at t_S can be easily understood as due to a collimated outflow (the j or J models). A radiative non-spreading jet interacting with $s \lesssim 3$ CBM could also accommodate

the steepening, if the CBM is a wind, but it is less likely that the radiative phase could last until later than 1 day after the burst.

050318. Because XRT observations started at $\lesssim 1$ h after the burst, the fast decay phase may have been missed. A steepening of the X-ray light-curve decay occurs at $t_S \sim 3 \times 10^4$ s without a spectral evolution. This steepening can be due to seeing the boundary of a jet (spreading or not). There are other possible models that can accommodate the steepening, all involving a variation in the CBM structural index S. They are the Sa outflow exiting a shell of a sharply increasing density and entering a r^{-2} wind and jc outflow transiting from a r^{-3} wind to a shell with sharply increasing density at t_S.

050319. This afterglow is similar to 050315, the hardening of the X-ray spectrum across the light-curve flattening, which occurs at $t_F \sim 400$ s, being stronger. Barthelmy et al. (2005) and Cusumano et al. (2005) have shown that the BAT GRB emission extrapolated to the XRT band matches the X-ray flux measured at 200 s. If the origin of time for the X-ray emission is set at the beginning of the second (and last) GRB pulse, then the decay index ($\alpha_1 = 3.0 \pm 0.2$) of the early X-ray emission is consistent with the expectations for the large-angle GRB emission ($2 + \beta_\gamma = 3.13 \pm 0.28$). However, the early X-ray spectrum ($\beta_1 = 1.94 \pm 0.20$) is rather soft compared to that of the burst. On the other hand, the substantial hardening of the X-ray spectrum across t_F, with $\beta_2 - \beta_1 = -1.15 \pm 0.23$, exceeds that which the passage of the cooling frequency through the observing band can produce ($\beta_2 - \beta_1 = -0.5$), suggesting that the X-ray emissions during the 1st and 2nd afterglow phases arise from different mechanisms. We note that the X-ray light curve for both phases may be explained in the structured outflow framework if we make the ad hoc assumption that the spectrum of the spot emission (dominating the afterglow flux before t_F) is softer than that from the surrounding outflow (which overtakes the spot emission after t_F).

The steepening of the X-ray light curve at $t_S \sim 3 \times 10^4$ s can be explained by seeing the edge of a jet (spreading or not), or with the jc model and a CBM structure changing from a r^{-3} wind to a homogeneous medium at t_S. All these models require a hard electron distribution, with $p < 1.7$.

050401. Although the XRT observations started 100 s after the burst, a steeply falling-off phase was not seen. Until $t_S = 5000$ s, it exhibits a decay so slow that it cannot be explained without energy injection or a structured outflow. The RSc model with energy injection requires too much energy, while the structured outflow does not satisfy condition (v) for the Rjc model. Then the steepening of the X-ray light curve at t_S can be understood as resulting either from the cessation of the energy injection or from seeing the outflow boundary. In the latter case, the light-curve decay should be steeper than for the S model and slower than for the j model. That the steeper decay after t_S can be accommodated by either the S or j models (Table 1) supports a structured outflow as the source of the X-ray light-curve steepening.

050408. This afterglow is very similar to 050401, except that the steepening occurs later, at $t_S \sim 10^5$ s. Its light-curve decay before t_S is also too slow and requires an energy injection episode or a structured outflow. The X-ray spectral slope after t_S is not known, but if we assume that there is no spectral evolution across t_S (as is the case for all other afterglows), then the light-curve decay index and spectral slope measured after t_S can be accommodated by the Sa and jc models. The RSc and Rjc models are also allowed, though it is unlikely that the radiative phase lasts until days after the burst.

050505. This afterglow is similar to 050318, its X-ray light-curve steepening at $t_S = 4 \times 10^4$ s without a spectral evolution. However, in contrast to 050318, the spectral slopes and decay indices before and after t_S cannot be reconciled within any model other than Rjc, even

if we allow for a varying CBM structure. Besides that the radiative phase is unlikely to last until 1 day after the burst, the *Rjc* model requires a r^{-3} CBM profile, for which the closure equations given in Section 2.3 are not accurate. Hence, it seems more plausible that the slow decay of this afterglow before t_S is due to energy injection or a structured outflow. The *Sa* model fails to satisfy conditions (v) and (vi) for these two case. As for the afterglows 050401 and 050408, the steepening of the X-ray light curve could then be attributed to the end of the energy injection or to the outflow axis becoming visible to the observer.

4 DISCUSSION

As shown in Table 1, the three decay phases of the *Swift* X-ray afterglows can be understood in the following way.

   (i) The hardening of the 0.2–10 keV spectrum of the X-ray afterglows 050315 and 050319 from $t < 400$ s (when a fast decaying X-ray emission is observed) to $t > 400$ s (when the X-ray light curve exhibits a slow decay) indicates that the early, fast falling-off X-ray emission arises from a different mechanism than the rest of the afterglow. Barthelmy et al. (2005) have argued that this mechanism is the same as for the GRB emission. The results of Tagliaferri et al. (2005) suggest that this explanation does not work well for the afterglows 050126 and 05018. In these cases, the steep X-ray decay requires a very narrow outflow whose edge is seen as early as 100 s after the burst, the following, slower decay phase being explained by energy injection in the blast-wave or by a rather contrived (see below) angular structure of the blast-wave.

   (ii) The X-ray decay measured until 1 h, 0.3 and 0.5 day for the afterglows 050401, 050408 and 050505, respectively, is too slow to be explained by the simplest blast-wave model. Such a slow decay can be produced by an outflow endowed with angular structure or by a continuous injection of energy in the forward shock.

   (iii) The steepening of the X-ray decay observed at 1 h to 2 day for the afterglows 050128, 050315, 050318 and 050319, i.e. at a time comparable to that of the steepening of the optical decay of many pre-*Swift* afterglows, can be explained by seeing the edge of a jet. For the remaining five afterglows, whose pre-break X-ray decay requires energy injection, the steepening can be attributed to the cessation of injection.

In the large-angle GRB emission model for the early, fast falling-off phase, the X-ray emission arises from the same mechanism as the GRB itself, but arrives at observer later because it comes from the shocked gas moving slightly off the direction towards the observer. For this model to be at work, three conditions must be satisfied. First, the 15–350 keV GRB emission extrapolated to the 0.2–10 keV X-ray band, under the assumption that the power-law burst spectrum $F_\nu \propto \nu^{-\beta_\gamma}$ extends unbroken down to 0.2 keV, should match or exceed the X-ray flux at the first epoch of observations. Secondly, the spectral slope of the early afterglow should be the same as that of the GRB. Thirdly, the X-ray light-curve decay index should be equal to $2 + \beta_\gamma$ (Kumar & Panaitescu 2000). For completeness, we present here a short derivation of this result. If the GR emission stops suddenly at some radius r and blast-wave Lorentz factor Γ, then the received flux is $F_\nu(t) \propto \mathcal{F}'_{\nu'}(d\Sigma/dt)\mathcal{D}^2$ where $\mathcal{F}'_{\nu'} \propto \nu'^{-\beta}$ is the outflow comoving frame surface brightness at frequency $\nu' = \nu/\mathcal{D}$, $d\Sigma = 2\pi r^2\theta \, d\theta$ is the elementary area whose radiation is received over an observer time dt, θ is the angle (measured from the direction towards the observer) of the fluid element from which radiation is received at time $t = r\theta^2/2$ (hence $dt \propto \theta \, d\theta$), $\mathcal{D} = 2/(\Gamma\theta^2) \propto t^{-1}$ is

the relativistic Doppler factor, and the expressions for $t(\theta)$ and $\mathcal{D}(\theta)$ have been derived for $\theta \gg \Gamma^{-1}$, i.e. for the large-angle emission. The last factor $\mathcal{D}^2$ in the expression of F_ν accounts for the beaming of radiation from a relativistic source. After substitutions, one obtains that $F_\nu \propto \nu^{-\beta} t^{-2-\beta}$.

Barthelmy et al. (2005) found that the above three conditions for the large-angle GRB emission as the source of the very early, fast X-ray decay are met for the afterglows 050315 and 050319. For two other afterglows, 050421 (Godet et al. 2005; Sakamoto et al. 2005) and 050713B (Page et al. 2005; Parsons et al. 2005), we find that their fast X-ray decays cannot be reconciled with their hard X-ray continua by any of the blast-wave models considered here, but they do satisfy the last two conditions above for the large-angle GRB emission interpretation. Tagliaferri et al. (2005) showed that the early X-ray emissions of the afterglows 050126 and 050219A are brighter than the GRB extrapolated fluxes and are softer than the burst emission, therefore their early X-ray afterglows cannot be immediately identified with the large-angle GRB emission. Kumar et al. (2005) discuss the conditions under which the fast X-ray decay of these last two afterglows can be reconciled with the large-angle GRB emission.

The outflow structure required to explain a light-curve flattening followed by a steepening must contain a bright spot (moving towards the observer) surrounded by a dimmer envelope where the ejecta have a lower energy per solid angle $dE/d\Omega$, so that the emission from the spot exhibits a fast decay after its boundary becomes visible. Further, the envelope should be embedded in a wider outflow whose emission overtakes that of the spot when the blast-wave Lorentz factor has decreased sufficiently. To explain the light-curve flattening, the $dE/d\Omega$ in this wider outflow should rise away from the spot as $\theta^{1/2}$ to θ^3, where θ is the angle measured from the outflow's symmetry axis. Finally, to explain the light-curve steepening, the $dE/d\Omega$ should stop increasing with angle (for the *S* model) or peak and then decrease (for the *j* and *J* models). The decrease could be gradual, with the X-ray light-curve steepening occurring when the fluid at the peak of $dE/d\Omega$ becomes visible and the outer outflow contributes to the post-break emission (this is the light-curve break mechanism proposed by Rossi et al. 2002). If the decrease of $dE/d\Omega$ is sharp, then the post-break X-ray light-curve decay will be faster, particularly if the outflow undergoes lateral spreading [this is the light-curve break mechanism proposed by Rhoads (1999)].

In the energy injection model, the forward shock energy increases due to some relativistic ejecta which catch up with the decelerating blast-wave (Rees & Mészáros 1998). The energy injection reduces the blast-wave deceleration rate and mitigates the decay of the afterglow emission. In principle, during the slow X-ray decay phase, there could be an energy injection for all afterglows considered here; Table 2 lists only the cases when it is required. As shown in Table 2, we find that, to explain the slow phase of the X-ray afterglow decay, the blast-wave energy should increase with observer time faster than $t^{0.5}$ and slower than $t^{1.5}$. The arrival of new ejecta at the forward shock could be due either to the spread in the Lorentz factor of ejecta released simultaneously (short-lived engine) or to a long-lived GRB engine, releasing a relativistic outflow for a source-frame duration comparable to the observer-frame duration of the slow X-ray decay phase. In the former case, the ejecta-forward shock contrast Lorentz factor is $[(4-s)/(1+e)]^{1/2} \lesssim 2$ (Panaitescu & Kumar 2004), where e is defined by equation (32), while in the latter case the Lorentz factor ratio can be much larger. Consequently, we expect that, for a short-lived engine, the reverse shock propagating in the incoming ejecta is only mildly relativistic and radiates mostly at radio

frequencies while for a long-lived engine the reverse shock could be very relativistic and radiates in the infrared optical.

As mentioned above, the early, fast decay of the X-ray afterglows 050126 and 050219A cannot be readily identified with the large-angle GRB emission and could be attributed to the forward shock. The fast X-ray decay displayed by these afterglows at $\sim$400 s can then be explained only within the structured outflow and energy injection models. In addition, two other afterglows, not considered in this work, 050712 (Grupe et al. 2005) and 050713A (Morris et al. 2005), exhibit an X-ray decay which is too slow and incompatible with the reported X-ray spectral slope, both requiring either an energy injection or a structured outflow.

For the afterglows 050128, 050318 and 050319, we find that a change in the circumburst density profile provides an alternate model to structured outflows and jets for the steepening of the X-ray decay observed by XRT after 0.1 day. For all the three afterglows, the changing external density corresponds to a transition from a r^{-3} wind to a region of uniform or increasing density. The r^{-3} density structure requires a time-varying mass-loss rate and/or speed of the wind of the massive star GRB progenitor, while the uniform or increasing density shell could result from the internal interactions in a variable wind (e.g. Ramirez-Ruiz et al. 2005). The self-similar solutions of Chevalier & Imamura (1983) for wind–wind interactions indicate that a uniform shell results from a substantial decrease of the star's mass-loss rate accompanied by a large increase in the wind speed. These major changes in the wind properties would have to occur $\sim$1 000 yr before the GRB explosion, if the radius where the r^{-3} circumburst density profile terminates is that of the forward shock at 0.1–1 day.

To answer the question of how can we distinguish between the above three models (energy injection, structured outflow and non-monotonic circumburst density) for flattenings and steepenings of the afterglow light curve, we note that, if the cooling frequency located between the optical and X-ray domains, each of those models yields a specific difference $\Delta\alpha_c - \Delta\alpha_o$ between the changes $\Delta\alpha_c$ and $\Delta\alpha_o$ of the X-ray and optical light-curve decay indices. Therefore, to discriminate among the few possible models discussed here, it is very important to monitor the optical afterglow emission over a wide range of times, from minutes to days after the burst.

5 CONCLUSIONS

The most often encountered feature resulting from the analysis of the nine X-ray afterglows analysed in this work is the existence of a substantial energy injection in the blast-wave at hours to 1 day after the burst. This energy injection is necessary to reconcile the slowness of the X-ray decay with the hardness of the X-ray continuum for five out of nine afterglows and is possible for the other four as well. The injection should increase the blast-wave energy as $t^{1.0\pm0.5}$, t being the observer time, leading to a shock energy which is eventually larger by a factor of 10–1000 than that at the beginning of the slow X-ray decay phase.

The exponent e of power-law energy injection identified in Table 2 is generally inconsistent with that expected for the absorption of the dipole radiation from a millisecond pulsar (see also Zhang et al 2005). In this case, an important energy input in the blast-wave is obtained only for the first few thousand seconds, when the pulsar's electromagnetic luminosity is constant (Zhang & Mészáros 2001), which leads to $e = 1$. Hence the energy injection must be mediated by the arrival of ejecta at the forward-shock.

If the GRB engine were so long lived that only a small fraction of the total outflow energy yielded the burst emission, then such a large

energy injection would imply an even higher GRB efficiency than previously inferred (above 30 per cent; Lloyd-Ronning & Zhang 2004) from afterglow energetics and would pose a serious issue for the GRB mechanism (Nousek et al. 2005). However, we cannot yet tell if the energy injection lasts for hours because the central engine is long lived or because there is a sufficiently wide distribution of the initial Lorentz factor of the ejecta expelled by a short-lived engine. In the latter case, the entire outflow could be emitting both the GRB and afterglow emission, and the GRB efficiency remains unchanged.

If the fast decaying X-ray emission preceding the slow X-ray fall-off arises from the forward shock as well, then energy injection must start at the end of the steep decay phase, i.e. it must be a well-defined episode. However, in this scenario the outflow must be very tightly collimated to yield a fast decay at only 100 s after the burst. The blast-wave Lorentz factor is $\Gamma(t = 100s) \simeq 100(E_{53}/n_0)^{1/8}$ (E_{53} being the shock energy in 10^{53} erg and n_0 the CBM particle density in cm^{-3}); thus the jet opening must be less than $\Gamma^{-1} = 0°.5$. Alternatively, the early, fast falling-off X-ray emission could be the large-angle emission from the burst phase, overshining the forward shock emission. This interpretation is favoured by Barthelmy et al. (2005) and Hill et al. (2005) for the afterglows 050117, 050315, 0509319, although for other afterglows (e.g. 050126 and 050219A; Tagliaferri et al. 2005) the spectral properties of the burst and X-ray afterglow emissions are not readily consistent with each other.

For a structured outflow to explain all the three decay phases of the *Swift* X-ray afterglows, the distribution of the ejecta kinetic energy with angle must be non-monotonic. This is somewhat contrived and inconsistent with the results obtained by MacFadyen, Woosley & Heger (2001) from simulations of jet propagation in the collapsar model. Thus, structured outflows do not appear to provide a natural explanation for the features of the X-ray afterglow light curves.

We note that the inferred indices of the power-law electron distribution with energy, which are given in Table 2, range from 1.3 to 2.8. One would have to ignore four of these nine *Swift* afterglows to obtain a unique electron index, $p = 2.1 \pm 0.1$. This is a puzzling feature of relativistic shocks in GRB afterglows: the shock-accelerated electrons do not have a universal distribution with energy, a fact which is also proven by the wide spread of the high-energy spectral slopes of Burst and Transient Source Experiment (BATSE) bursts ($\Delta\beta \simeq 2.0$ in fig. 9 of Preece et al. 2000), which is equal to $p/2$ or $(p - 1)/2$, and by the wide range of the optical post-break decay indices of the BeppoSAX afterglows ($\Delta\alpha \simeq 1.6$ in fig. 3 of Stanek et al. 2001 and in fig. 2 of Zeh, Klose & Kann 2005), which is equal to p. However, from the X-ray spectral slope of 15 BeppoSAX afterglows, De Pasquale et al. (2005) conclude that the electron index p has a universal value of $p = 2.4 \pm 0.2$ (see their fig. 3).

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